DOCUMENT RESUME

ED 147 109 SE 023 259

TITLE	Retrofitting: The Thermal Upgrading of Buildings.
INSTITUTION	Maine Audubon Society, Falmouth.
SPONS AGENCY	Office of Education (DHEW), Washington, D.C.
BUREAU NO	522AH60802
PUB DATE	Sep 77
GRANT	G007602036
NOTE	31p.; For related documents, see SE 023 258, 370-371; Figures 1-5 removed prior to being shipped to EDRS for filming due to copyright restrictions; Not available in hard copy due to marginal legibility of original document
EDRS PRICE	MF-$0.83 Plus Postage. HC Not Available from EDRS.
DESCRIPTORS	*Building Design; Building Improvement; *Climate Control; Design Needs; Energy; *Energy Conservation; *Environmental Education; Speeches; *Thermal Environment
IDENTIFIERS	Environmental Energy Education Project

ABSTRACT

This publication is a compilation of talks delivered during the spring of 1977 by Charles Wing. Contents of the booklet include retrofitting old houses, condensation and vapor barriers, solutions to the vapor barrier problem, and how much of which insulation to use. The publication includes charts, drawings, and equations to illustrate the topics being discussed. Life cycle cost analysis is utilized in the section dealing with determining the amount of insulation to be used. (Author/MA)

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RETROFITTING: THE THERMAL UPGRADING OF BUILDINGS

This booklet is a compilation of talks delivered during the Spring of 1977 by Charlie Wing. Wing is the founder and director of Cornerstones, a school for owner-built homes, located in Brunswick, Maine. In addition to preparing these lectures, Wing has been a consultant in the preparation of many of the EEEP materials.

Jonathan Gorham
EEEP Director

September 1977
Falmouth, Maine

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The activity which is the subject of this report was supported in part by a grant from the Office of Education, U.S. Department of Health, Education and Welfare. However, the opinions expressed herein do not necessarily reflect the position or policy of the Office of Education and no official endorsement by OE should be inferred.

Grant #G007602036
Project #522AH60802

RETROFITTING OLD HOUSES

Retrofit is a new word meaning raising the performance standards of an existing house. It is quite different from restore, remodel, or redecorate. Some of the reasons for carrying out such an ambitious program include:

- repairing a damaged or distorted structure
- modernizing plumbing
- modernizing electrical wiring
- reorganizing interior space and traffic pattern
- changing the primary heat source
- reducing annual energy consumption

All of the above are best done concurrently, but my purpose here is restricted to the last item.

When we speak of energy consumption in Maine, we are chiefly referring to the annual house heating bill, although the heating of domestic hot water is also important. In order to discuss heat intelligently, we must understand the ways in which heat moves from inside spaces to outdoors.

Heat is transferred in three different ways: conduction, convection, and radiation. An example of conduction is the warm silver teaspoon handle when used to stir coffee. Conduction is the transfer of heat by a solid material. Materials which transfer heat readily are known as conductors and those which do not are insulators. Metals are the best conductors; dead air and materials trapping dead air are insulators.

Convection is the transfer of heat by a moving fluid. A convection which works for us is the draft in a chimney. A convection which is not so pleasant is the cold draft under a windo. in the winter. Both of these convections are due to the force of gravity on air: warmer air is less dense and therefore rises; cold air is more dense than the surrounding air and falls.

Radiation is the transfer of energy through space. Since ordinary air consists mostly of space, radiation is very effective through air: all objects continually radiate energy in proportion to their temperatures to the fourth power. Radiation is therefore extremely temperature dependent. An outstanding example of radiation is that given by the wood stove.

All of the above mechanisms are continuously at work, transferring heat through the various surfaces of a house from the warmer side to the cooler side.

A special case of convection is usually singled out -- infiltration. Infiltration is the physical replacement of warm inside air by cold outside air. It occurs primarily under the pressure of wind through cracks around doors and windows. It deserves special attention because it alone accounts typically for 20-40% of the total heat loss.

Now the heat loss of a house and the projected fuel saving from any operation changing the heat loss characteristics of a house can be found in a fairly precise manner by a rather elaborate set of calculations as set forth in a number of recent books. However, the average homeowner, I'm afraid, will regard such calculations in much the same light as the annual income tax form. Fortunately, the government has come up with the equivalent of a "short form" energy calculation. This document, entitled In the Bank or

Up the Chimney?, is easily mastered by the least mathematical. By a series of step by step decisions and consultation of tables, the homeowner is led to the end result: the financial payback period of various retrofit options.

I have just extensively retrofitted a typical 100-year old farmhouse of 1500 sq. ft. area in Brunswick, Maine. I used In the Bank or Up the Chimney to confirm my intuitive assumptions that all the operations performed were economically justified.

To use the step-by-step calculation procedure in the book, you first need to characterize the building before retrofit. My building looked as follows:

- 1500 SQ. FT. TOTAL LIVING AREA (2 floors)
- 1600 SQ. FT. OUTSIDE WALL AREA
- 100 linear feet of perimeter
- 13 windows, double hung, no storms
- 2 doors, no storms
- no insulation anywhere
- crawl space foundation
- previous fuel bill 2000 gal. #2 oil/year

The table below shows the operations performed, cost of material, cost if contracted (I did it myself), first year fuel saving, lifetime fuel saving, and payback period in years. Each of the above are separately calculated for wood, oil, and electricity as the primary fuel. I use wood.

TASK	Cost of Material	Contracted Cost	1st Year Saving ($)	Lifetime Saving ($)	Payback Period (Yr.)		Fuel WOOD = $60/cord OIL = $.40/gal. ELECT. = 3¢/KWHR
Insulate attic with R19 insulation (6" Fiberglass)	$160.	480.	142.	1846.	1.1	3.3	WOOD
			213.	2769.	0.8	2.4	OIL
			497.	6461.	0.3	0.9	ELECTRIC
Insulate crawl space with R11 insulation (3½" Fiberglass)	40.	120.	22.	286.	1.8	5.4	W
			32.	416.	1.2	3.6	O
			76.	988.	0.5	1.5	E
Insulate walls with 4" urea-formaldehyde	800.*	800.	123.	1599.	6.5	6.5	W
			185.	2405.	4.3	4.3	O
			431.	5603.	1.9	1.9	E
Weatherstrip doors and windows	100.	300.	57.	741.	1.7	5.1	W
			86.	1118.	1.2	3.6	O
			200.	2600.	0.5	1.5	E
Add storm doors and windows	150.	450.	41.	533.	3.7	11.1	W
			61.	793.	2.5	7.5	O
			144.	1872.	1.0	3.0	E
Totals	1250.	2160.	385.	5005.			W
			577.	7501.			O
			1348.	17,524.			E

CONDENSATION AND VAPOR BARRIERS

Introduction

Of the 80 million homes in the United States, probably less than one half have any insulation at all. Insulation as we presently know it didn't exist until 1950. A large percentage of existing homes were build in the two decades from 1950 to 1970 with only token insulation in walls and ceilings and none at all in the basement. How could this have happened? Strange as it may now seem, during the twenty year period 1950-1970, energy costs actually increased less rapidly than inflation while construction costs rose more rapidly. In other words, energy costs became less significant in the overall costs of running a house.

1970 now seems ages ago, particularly to those living in rambling uninsulated houses. It was an age ago. As far as energy is concerned, we have stepped into the post-industrial age, an age to be characterized by head spinning increases in energy costs. Space heating will compete with transportation and manufacturing for the dwindling convenient fossil fuels. When supply is fixed and demand increases, prices tend to rise faster than general inflation. The price of land provides a good example. Supply and demand forces on fossil fuel energy prices are even stronger. The supply is not fixed in the same sense as land but actually decreasing as we consume and thereby destroy the resource. In any case, there is little question that energy prices have just begun a price spiral the likes of which the world has never seen. The time has come to retrofit.

Retrofit

"Retrofit" is an unfamiliar term heard more and more. It is perhaps best defined by what it is not.

It is not restoration - restoring a thing to a former condition.

It is not reproduction - making a copy.

It is not redecoration - embellishing; beautifying.

It is word used previously by the aerospace industry to describe modification of earlier equipment to present standards. The term has been adopted by the federal government to connote doing whatever possible to decrease the energy consumption of buildings: insulation, weatherstripping, double and triple glazing, solar collectors, window shutters, and conversion to other fuels.

According to the latest public opinion polls, a majority of Americans finally believe that the energy crisis is real and will impact them personally in the years ahead. A year ago the question was, "Can I afford to insulate my house?" Today the question is, "Can I afford not to insulate?" The obvious answer to increasing numbers is "Nc". Insulation contractors are springing up like fruit flies. Bread trucks criscross the countryside with signs proclaiming "Save 30,50,60% of your fuel bill." Contractors are stuffing and blowing Fiberglas, foam and shredded newspaper (under the more acceptable alias of cellulosic fiber) into every nook and cranny. Will you really save 30 - 60% of your fuel bill? You bet you will. In fact, you should, in most cases, be installing even greater amounts than the manufacturers are promoting!

But hold on a moment. We are talking about possible modifications to a $30,000 - $100,000 structure resulting in potential lifetime operating savings of the same magnitude.

Most Americans are confronting the largest single economic decision of their lives with less information than provided by an encyclopedia salesman.

And consumers are not alone. Would you believe that rehabilitation officials and even insulation contractors themselves generally lack the information required to make optimal decisions? Folks, we've got problems!

The two questions I am most often asked are: 1) Is it safe to blow insulation into existing walls without tearing out the plaster and installing a vapor barrier? 2) How much of what kind of insulation should I install?

VAPOR BARRIERS AND CONSENSATION IN WALLS

Water exists in nature in three states: solid ice, liquid water, and gaseous water vapor. The first two are familiar because we've seen them. No one has ever seen water vapor because, like all the other gases constituting ordinary air, it is invisible. We often think we're seeing water vapor coming out of the tea kettle, but we're too late. The steam that we see is condensed water vapor - tiny droplets of liquid water formed whenever the concentration of water vapor is excessive.

Ordinary air always contains some water vapor. Liquid water is constantly evaporating. Boiling spaghetti pots, how showers, clothers driers and house plants are prodigious sources of water vapor. If water vapor were a colored gas it would be very easy to visualize its movement about a house.

I want you to join me in a little experiment. Don't get up from your chair! This sort of experiment is terrific in that it requires no equipment, no computers, and no federal funding. Join me in Figure (1). We have drilled a hole in the ceiling of a room. Look down and you will see a group of people wearing white hats in the next room. A significant fact is that the two groups of people are unaware of the colors of each others' hats. In fact they perceive no difference at all.

Now cover up the hole for an hour and speculate as to what you'll see when you next look. Hour's up. What do you see? You were right - the black and

white hats are randomly distributed throughout both rooms. Both groups have spread out randomly simply because nothing prevented them from doing so.

In scientific parlance the random motion of things toward a more uniform distribution is called diffusion. It naturally results in net movement from areas of higher to areas of lower concentration, leading to the concept of a vapor pressure in the case of gases.

As the third step in our experiment, lets open a large garage door to the outside world containing, by the way, a very large number of white-hatted people. After the second hour, what do you see? I'm sure you'll agree that the relative number of black hats in the room with two doors has decreased. Some of the black hats have simply migrated out through the garage door.

I'm sure also that you have already guessed that the white hats are air molecules, the black hats water vapor molecules, and the room with two doors the empty space in an uninsulated wall. Thank you for joining me in this very significant experiment.

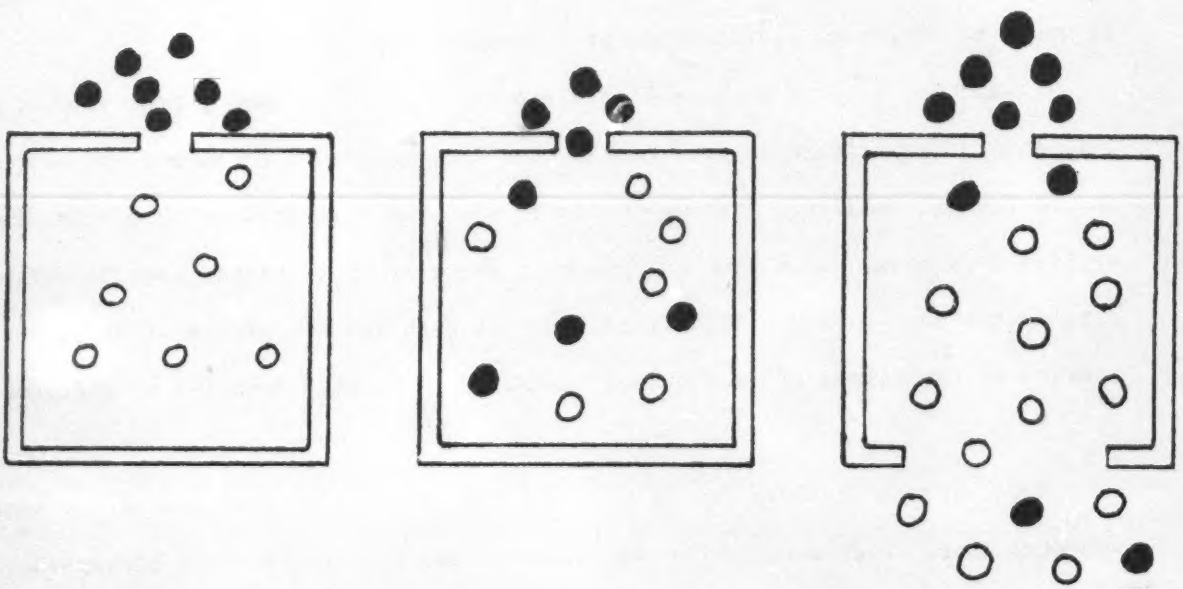

figure 1

When the concentration of water vapor in air is too high, water vapor molecules begin to stick together and form droplets of condensation. "Steam" from the tea kettle, clouds in the sky, fog, and dew drops on grass are all examples of condensed water vapor. Figure (2) shows that the amount of water vapor air can hold depends upon air temperature. The saturation curve shows that air can hold more vapor at higher temperatures. At any specific temperature the amount of vapor in the air divided by the amount possible, expressed as a percentage, is the relative humidity. Simply cooling a volume of air would cause it to move to the left horizontally (toward lower temperature) from point A to point B. At point B the relative humidity is 100% and the air has reached its dew point temperature. Cooling the air further will result in condensation as the point describing the air moves from B down the saturation curve.

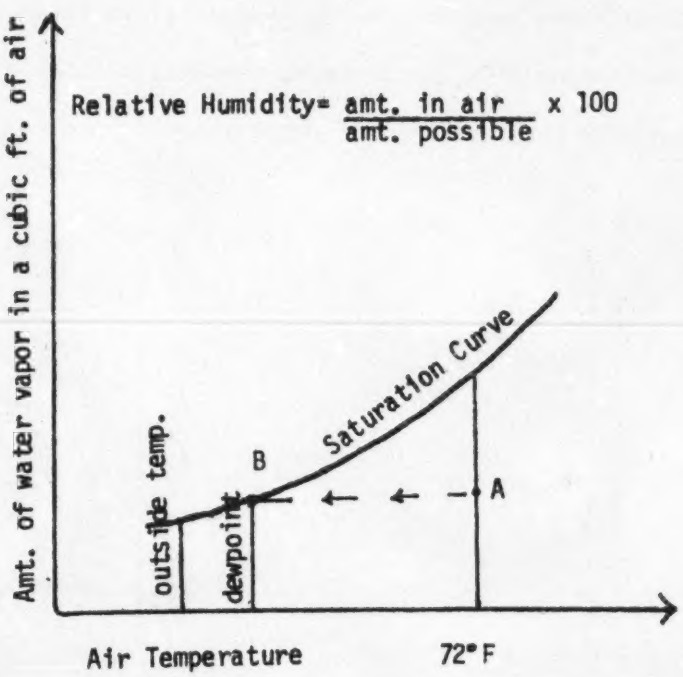

figure 2

To what extent does this process occur in house walls? In Northern New England and any other area having more than 6000 degree days, even with an inside relative humidity of as little as 20%, the temperature drop from inside to outside is so consistently great during the coldest months that condensation is a continuous process. If you have opened a wall or entered the attic of an old farmhouse in January you have seen the frost crystals on the inside of the wall or roof boards.

If condensation is so bad why have old farmhouses stood for 100, 200 or even more years with so little damage? The damage caused by condensation is indirect. Condensation simply provides one of the necessary conditions for dry rot. Dry rot is a misnomer. The necessary conditions for this wood devouring fungus are: moisture (condensation), wood (joists, rafters, and sills), absence of light, and a temperature of 50°F.

Figure 3 shows the wall cavity of an old uninsulated house. The inside temperature is 70°F and the outside air 20°F. Even though the relative humidity is probably lower inside than outside, the concentration of water vapor inside is greater due to evaporation from hot showers, cooking, clothes drying, plant evapotranspiration, and the breathing of people, not to mention a possible humidifier.

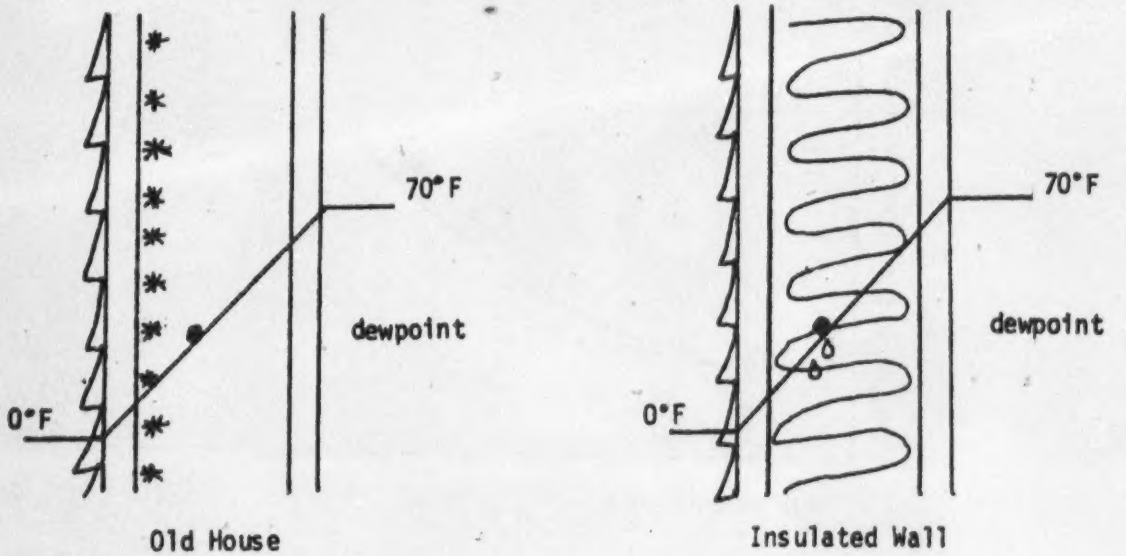

figure 3

Therefore, the general migration of water vapor is from inside to outside through the various house surfaces. The concentration and therefore migration is greatest in source areas such as bathrooms, kitchen, and greenhouse. All winter long the frost in the walls builds up, but what happens? Nothing, because the temperature inside the wall and attic is below 50°F. The dry rot fungus is, in effect, in the refrigerator over the winter. Finally, comes the spring and blessed average temperatures over 50°F. But by this time the frost has melted and the moisture whisked away by the outside air which so readily moves through the drafty old walls. By this fortuitous combination of climate and drafty construction has been saved the architectural heritage of New England.

Now comes the insulation man in his bread truck bearing sacks of cellulosic fiber, barrels of what appears to be shaving cream, and promises of fuel savings of 50%. Up go the ladders; whirr go the drills; and the insulation is pumped into previously empty walls. The next winter things are slightly different. Inside temperatures are slightly higher, outside temperatures low as ever, and the relative humidity a little higher due to a tighter house. Inside the wall the same old condensation is occuring but instead of condensing as frost on the wall boards the water vapor is now condensing in something resembling a sponge - the insulation! All winter long the insulation soaks up condensate. In extreme cases, water can actually be wrung from the insulation. Of course the dry rot is still inactive at this point. But now more bad news. Spring with attendant average daily temperatures over 50°F arrives but the insulation is still wet. The insulation has soaked up more moisture than the previous empty wall and by its presence has reduced the circulation of drying air. We are trying to dry the wash by hanging it in the closet! In a bad situation moisture could be present inside the wall until June or July when, in the case of a sunlit wall, interior temperatures as high

as 100°F may occur. By such an unfortunate combination of circumstances will be lost some of the jewels of the New England countryside.

Vapor Barriers

We have seen what happens when water vapor migrates from inside to outside of a cold wall space. What happens when the migration is reversed? Diffusion is a relatively slow process. Convection or general movement of an air mass can easily overcome diffusion. Think of it as water vapor molecules paddling their canoes upstream against the general drift of air molecules. Referring to Figures 2 and 3, you should easily see that condensation will never occur when the general air motion is from outside to inside. Regardless of outside conditions, relative humidity will decrease as the outside air is progressively warmed toward the living space. Since initial relative humidity cannot, by definition, exceed 100%, the dewpoint will never occur inside the wall. If we were sure that the air in a wall cavity originated from outside the building, we could be equally sure that the wall was safe from dry rot (barring another source of water in the wall such as ice dams or backed up gutters). Architects use the general "rule of five" that the permeance (air leakiness) of the outside wall surface should be a least five times that of the inside surface. In terms of our experiment, if the garage door leading to the outside were at least five times as large as the smaller door, we would be sure that the build up of water vapor in the space would be insufficient to result in condensation. This is also referred to as "relieving the vapor pressure".

All building materials impede the diffusion process to some extent. However, over the long heating season, it is the relative permeance which counts. Materials used specifically for their ability to stop water vapor are known as vapor barriers. The relative permeance of common building materials are shown in Table 1.

TABLE 1

Permeance of Building Materials

Vapor Barriers	1 mil aluminum foil	0.00
	6 mil polyethylene	0.06
Paint and Wallpaper	2 coats shellac or varnish on wood	0.5
	vinyl wallpaper	1.0
	3 coats oil paint on wood	1.0
	2 coats oil paint on plaster	2.0
	3 coats latex on wood	10.0
	ordinary wallpaper	20.0
Rigid Insulation	1" urethane	1.0
	1" styrofoam	1.0
	1" bead board	4.0
	1/2" insulating board	50.0
Masonry	4" brick	1.0
	8" concrete block	2.0
Papers	builders foil	0.2
	15 lb. tarpaper	18.0
	builders sheathing paper	40.0
Other	1/2" CDX plywood	0.5
	3/4" board	3.0
	plaster	20.0
	gypsum drywall	50.0

The "rule of 5" applied to Table 1 indicates that the permeance of the outside wall skin must be a least 5 times the permeance of the inside skin to avoid wall cavity condensation. Use of the table assumes no holes or cracks in the material which are not filled or repaired. To assume that a polyethylene or foil vapor barrier with 2" x 4" electric receptacle holes is still an acceptable vapor barrier is akin to assuming that a boat with holes drilled in the bottom will float. Somewhere along the line the sponsors of the National Electric Code and the various building codes should get together to resolve this dilemma.

Example: Suppose in removing a clapboard you discover your wall to consist of oil painted clapboard, tarpaper, 3/4" board, empty space, and plaster and lath. This wall does not conform to the rule of 5 since the painted clap-

board, if tight and sound, is far less permeable than the plaster wall. Simply insulating this wall without installing a vapor barrier may very well result in ultimate destruction of the wall through dry rot. If you discover plywood under the clapboard, you're in even greater trouble. In doing more comparisons, you'll find that simply blowing insulation into most existing wall cavities without further attention to relative permeance is a very dubious practice.

The construction in the example is very typical of houses build before 1950. Plywood will often be found in houses built after 1950. Neither of these constructions are acceptable without modification for blown insulation. Both government and industry know this but stop short at simply stating that vapor barriers should be installed on the warm side of any insulation. Batt and blanket Fiberglas insulation is labelled with elaborate and conspicuous instructions regarding installation of insulation and vapor barriers. But, Fiberglas can only be installed in open walls, where inclusion of a vapor barrier is a simple and inexpensive job. Blown Fiberglas, cellulose and foams are usually installed by contractors who invariably play down the dangers of condensation. Some contractors simply don't understand the problem; some lie; but most I believe rationalize.

On the one hand there is almost a wartime priority to conserve fuel by insulating existing houses. On the other hand, when such insulation requires anything beyond simply lifting the telephone and having a crew arrive, drill and plug holes in the outside wall, cleanup and leave all in one day, most homeowners will not act. The contractors know it and the federal government knows it. We are caught between the proverbial rock and a hard place. I believe the average homeowner deserves better information. This is a serious question which the government, the building industry and the various building codes should address.

SOLUTIONS TO THE VAPOR BARRIER PROBLEM

It has been known that membrane-type vapor barriers are required in northern areas of the United States in any insulated section of house separating the inside and outside environments. Actually what is required is a ratio of permeance between outside and inside surfaces at least five. The polyethylene vapor barrier came into use at the same time as CDX exterior-sheathing, because it was virtually the only cheap and easily installed material at least 5 times less permeable than plywood.

Houses built before 1950 generally are not sheathed with plywood, but neither do they have vapor barriers. Installing blown-in insulation without regard for the "rule of 5" of relative permeance is very dangerous in areas with more than 5,000 heating degree days. In spite of the known dangers, very few homeowners are willing to gut the interiors of their houses in order to install the ideal vapor barries. For this reason I have compiled a list of steps, short of gutting, which should be considered by anyone insulating a previously uninsulated house in northern states. I list them in order of increasing effectiveness.

#1. Change your habits. Become aware of sources of water vapor in the house. Purchase a relative humidity indicator and try to keep humidity at 20% during the coldest months.
Humidifiers are out. Cook with lids on pots; shower with the bathroom window open and door closed; don't dry firewood inside. Reduce the number of house plants and/or switch to plants suited to dry climates such as cacti (dry climate plants are characterized by small, waxy, hard leaves).

#2. Check the basement as a source of moisture. A damp basement is a prodigious source of moisture for the house above. Water vapor is

lighter than air and migrates upward most easily. If you have a high water table or clay soil around the foundation wall, chances are you have a damp basement, clay floors, so typical of old farm houses, are especially bad. One solution is to cover the floor with a vapor barrier. Over a clay floor: level the floor; remove sharp objects; if really wet, install a drain tile and sump pump around the perimeter; lay down a continuous 6 mil polyethylene sheet (available up to 40' x 100'), and cover with sand and screened pebbles or a concrete slab. A second solution is to simply turn the cellar into a root cellar. Insulate the underside of the first floor with a vapor barrier facing up. Provided the basement walls are tight against infiltration, the cellar will run slightly below well water temperature or 35 - 40 degrees F in Northern New England. The heating bill of the house will also drop. However, don't forget to open the basement vents when spring arrives to prevent summer dry rot in the sills and joints.

#3. Tighten up the inside wall surface. The permeability of the inside wall surface can be lowered by a variety of treatments. Definitely cover kitchen and bathroom walls with vinyl wall paper. Lap the paper up against door and window frames. Don't forget the inside of cabinets and closets. Under the kitchen sink is especially important. When you encounter an electrical receptical, remove the cover plates, paper over the outlet, replace the cover plate with silicone or bathtub caulk, and only then carefully cut out the wallpaper away from the prong holes. Fill unused receptacles with plastic caps. DON'T FORGET TO TURN OFF THE ELECTRICITY FIRST.

Paint ceilings and other non-vinyl wallpapered walls with several coats of special vapor barrier paint. White shellac sealer/primer is

very effective and inexpensive. Check the compatibility of the proposed top coat with primer.

Caulk around the inside of all door and window frames. Cut off the cord on old windows with sash weights and tape over the pulley with duct tape. Remove all electrical cover plates and caulk with silicone as in the kitchen and bathroom.

In general, consider your house a boat about to be launched. Will it float? As you check its integrity, square foot by foot, the probable leaks will become obvious. Close your eyes and you will visualize water spouting from a wall receptacle as the house sinks. Tightening the inside defense results, as an added benefit, in a significant reduction of infiltration heat loss.

#4. Resurfacing. If the walls and ceilings are not exactly in House Beautiful condition, you might consider this surprizingly inexpensive but temporarily disruptive option. Professional remodelers find it least expensive to apply drywall (sheetrock) right over existing plaster walls. The cost, including material, insullation, taping and sanding, comes to about $.30 per square foot of material used. A typical house requires one week of work and when finished appears to be a brand new house ready for the painters.

First turn off the electricity, remove the electrical cover plate and receptacle or switch shimmed forward by a 3/8" spacer around the long screws and avariable speed drill with a Phillips bit. With plaster and lathe walls there is no need to locate the studs. On a newer house you have the rare opportunity to go around knocking holes in the walls with hammer or crowbar. If your

wiring isn't up to snuff, this is a perfect time to rewire as the holes won't have to be patched. Door and window moldings usually project 3/4". Careful drywall insullation will not require new moldings. I think the moldings look a lot better projecting only 3/8"!

#5. Venting the outside wall. Screened or louvered plug vents are available from hardware and lumber stores to increase the ventilation on the outside wall. Installation consists of simply cutting a hole of a specified size with either drill or hole saw in the top and bottom of each stud space and inserting the plugs. This is an extremely effective measure which has been used for years to release moisture and stop paint from peeling.

When insullation contractors blow in insulation from the outside, they drill holes in the top and bottom of each stud space to insert their nozzles. It is customary to then plug these hole with corks and replace the shingle, clapboard or other siding, leaving no trace of their work. This is an extremely stupid and damaging practice. It will cost little if any more to drill through both exterior finish and boarding and to plug the hole with a ventilating plug rather than a cork!

While on the general subject, it is worth sounding several more alarms. Vinyl and aluminum siding are both promoted as ending your painting chores forever and significantly reducing your fuel bills. Both are technically correct but misleading. By solving a peeling paint problem with vinyl or aluminum siding, you are sticking your head in the sand; you are curing a cancer with an aspirin. Paint most often peels because of excessive wall cavity moisture. Rather than releasing the moisture, vinyl siding merely conceals it. A further problem with these sidings is the sometime practice of first installing aluminum builders foil as an insulation. The insulation value of either the foil

and air space or 1/2" fiberglass batt under the siding is roughly 10% of that achieved by wall cavity insulations. Furthermore, aluminum foil is a vapor barrier. There is no more dangerous practice than using aluminum builders' foil under siding as a substitute for builders' paper because there is simply no way the rule of 5 can be achieved.

#6. Gutting. Gutting, or removing all of the inside finish to expose the studs and ceiling joists, is an extreme measure, but, is sometimes justified. Gutting allows:

- installation of a brand new surface
- installation of a proper vapor barrier
- inspection and repair of structual members
- new plumbing
- new wiring
- installation of the lowest cost insulation - fiberglass
- rearrangement of interior - space

If enough of the above operations are called for in your house, gutting is justified.

There is a right way and wrong way to gut. The wrong way consists of exploratory surgery - a very indecisive removal of one wall or ceiling at a time. It is caracterized by negative feelings. The feeling is " Oh no! It looks like we'll also have to do the ceiling now that we've removed the wall!"

The right way is prior commitment to radical surgery - and a battle plan. Every blow of the sledge hammer is accompanied by positive feelings-feelings of accomplishment. Proper equipment consists of heavy gloves, hard-hats, goggles, dust masks, chain-saw, wrecking bars, sledge hammer, nail

pullers, wheelbarrow (with solid tires), shovels and a loud radio. Proper timing is spring or fall when you can work with open or missing windows and doors without either sweating or freezing. That way air remains relatively clear as the wind blows through the open structure. Proper budget consists of a second mortgage or line of credit sufficient to cover labor and materials figures at about $5.00 per square foot gutted each.

Several other points learned the hard way are:

- Make sure all of your workers have tetanus shots.
- Insist on shoes with safety or at least very thick soles.
- Have a plan for rubbish removal - rent an old dumptruck and park it under a window with sash removed.
- Draw a plan showing original structure and planned modifications.
- Don't try to live in the house at the same time: You'll appreciate getting away from grime at the end of the day.

HAPPY GUTTING!

HOW MUCH OF WHICH INSULATION?

Introduction

Assuming you have already decided to insulate either a new or old structure and the vapor barrier situation has been resolved, the obvious question is, "How much insulation is economically justified?" That is easily addressed by the science of economics, provided reasonable projections of future fuel costs can be made.

Life Cycle Cost

Most Americans are accustomed to basing economic decisions purely on first cost. First costs are easily comprehended: How many dollars do you have to lay on the table? However a businessman operating on such a naive level would soon be forced out of business. The true cost of anything is its life-cycle cost - the cost of buying, maintaining, financing and fueling the thing over its lifetime. Some purchases are complicated. Insulation is not. Insulation you simply buy, usually on a cash basis, and it simply pays you back every year in fuel dollars.

Optimizing the Insulation

Figure 1 is a graph of inches of insulation vs. dollars per square foot of a house surface (wall, floor, or roof). Line A represents the installation cost. When a contractor estimates the cost of insulating your house the two big factors are: a) set-up cost, or the cost of simply getting to the job and setting up the equipment and b) the cost per board foot (1 sq. ft. x 1 inch)

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INSULATION THICKNESS.

of material used. Therefore, A is a straight line starting above zero at the set up cost. Curve B represents fuel dollar savings due to insulating one square foot of surface. By not insulating at all the saving is zero; by adding just one inch of insulation the heat is typically cut in half; in going from inch 19 to inch 20 the savings is very small. Therefore, curve B rises very rapidly from zero but flattens out, approaching the horizontal at large thicknesses. Of course the insulation "pays for itself" all the way in to the point where curves A and B cross. But that is not the optimum point. We are not looking for the thickness which just pays for itself after 20 years. Rather, we are looking for the thickness at which the bulge between curves A and B is maximum - that is, the thickness resulting in the maximum net saving. That is the optimum thickness.

Now economists have developed a neat trick to find that precise point. The trick is called marginal cost analysis. Line C represents marginal cost - the additional cost of one additional inch of insulation: If line A is straight, then line C is also straight and a constant. For example the marginal cost of installing yourself one square foot of fiberglass batt one inch thick is 3¢. Curve D is marginal saving - the additional saving due to the one additional inch of insulation: It starts high and tends toward zero. What makes marginal cost analysis so valuable is the fact that the optimum point is located at the intersection of marginal cost and marginal saving. It is easy to see that this is true. If we added too much insulation the additional (marginal) cost would exceed the additional saving. If we added too little insulation; there would yet remain potential net savings.

Therefore:

$$\text{Life Cycle Cost/Sq. Ft.} = \frac{24 \times DD \times F \times PWF}{10^5 \, R} + A_0 + A_1 R + A_2 R + A_3 R \qquad (3)$$

where: A_0 = insulation contractor set up charge/Sq. Ft.

A_1 = insulation cost per unit R

A_2 = extra structural framing cost per unit R

A_3 = value of space occupied by insulation per unit R

The optimum value of R is that which results in the minimum LCC and is found by differentiating LCC by R and equations to zero

$$\frac{\Delta \text{ LCC}}{\Delta R} = -\frac{24 \times DD \times F \times PWF}{10^5 R^2} + (A_1 + A_2 + A_3) = 0 \qquad (4)$$

$$R_{opt.} = \sqrt{\frac{24 \times DD \times F \times PWF}{10^5 (A_1 + A_2 + A_3)}} \qquad (5)$$

We note in passing that the two terms in Equation (4) are marginal saving and marginal cost respectively. Before we can turn the crank and find R opt we must find values for PWF and the three construction terms A_1, A_2, A_3.

PRESENT WORTH FACTOR

The PWF is the value in real or present dollars of future monies. As fuel prices increase, future savings increase. However, as inflation occurs, future value decreases. The PWF or present worth of fuel dollars saved over a period of years is

$$PWF = \sum_{t=1}^{N} (1 + P/1 + D)^t$$

where: Σ indicates the operation of summing N values of the term in parentheses while t increases from 1 to N.

t increases from 1 to N.

N = number of years (lifetime)

P = percentage annual rate of fuel price increase

D = discount rate (percentage interest rate of competing investments)

Obviously PWF is more simply a function of the difference between P and D. Therefore PWF is not so much a function of general inflation as a function of the rate of increase of fuel price relative to inflation. Table 1 lists PWF for several lifetimes N and differences (P-D).

TABLE 1 PWD

N	0%	1%	2%	3%	4%
10 yr.	10	10.46	10.95	11.46	12.01
20	20	22.02	24.30	26.87	29.78
30	30	34.79	40.57	47.58	56.09
40	40	48.89	60.40	75.40	95.03

Values of A_1, A_2, A_3

A_1, A_2, and A_3 are all related to the specific insulation material used. A_1 is easily found from suppliers or contractors as the cost per R. Since A_1 includes contractor markup it differs for owner installed vs contractor installed. A_2 is the extra cost of framing the house attributed to the presence of the insulation. Since certain minimum framing dimensions are required for structural strength independent of insulation; A_2 is taken to be zero up to those dimensions. A_3 accounts for the loss of valuable interior floor space to thicker wall construction: A_3 is assumed zero when the insulation is installed outside the foundation line.

Results

Figures 2, 3, 4, and 5 present the results of calculations of optimum thickness and life cycle costs at the optimum thicknesses for several types of construction, seven commercially available insulation materials and two different economic assumptions. In each of the figures the upper graph assumes the PWF calculated from a 20 year life and a fuel price increase rate of inflation plus 1%. The lower graph assumes 30 years and inflation plus 3%. I personally lean toward the latter. The left part of each graph assumes all of the labor is supplied by the owner, while the right side assumes a contractor built home. In all of the graphs the columns are broken into three levels representing wood, oil, and electric heat respectively at $ .30, $.50, and $1.00 per therm($10^5$ Btu) delivered. The height of the column is read on the scale to the left as total life cycle cost (installation plus fuel) for one square foot of the construction. The numbers on each column gives the optimum thickness of insulation in inches.

The results speak for themselves. Studying the results will produce several interesting observations:

a) HUD Minimum Property Standards, while in general agreement with these results, should be used with awareness. In general the proposed standards are deficient for electric heat, but excessive for wood heat.

b) The high technology, high priced foams are not justified except in conventional stud walls where the cost of the foam is balanced by the cost of the lost space.

c) As a rule of thumb, fiber glass blanket and bolt insulation and wood heat is the combination resulting in the lowest life cycle cost. The difference between wood/fiberglass and electric/urethane is as high as 5:1.

d) While the optimum point is mathematically unique, deviating from the optimum is not serious. For example, reducing attic insulation from an optimum of 18" to 12" results in an increase of life cycle cost of less than 5%. Further reductions result in rapidly increasing life cycle costs. As a rule of thumb then, reductions of up to 1/3 are not serious.

e) This paper hasn't addressed the qualities of the various insulations with the exception of R factor and cost. Other considerations to be aware of include a flammability, moisture resistance, insect resistance, settling with moisture and age, and environmental cost of production. We'll leave those questions for another time and forum.

FIGURES 2, 3, 4, and 5 REMOVED PRIOR TO BEING SHIPPED TO EDRS FOR FILMING DUE TO COPYRIGHT RESTRICTIONS.